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IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.Doi Number

Development and Testing of A Wearable Vibrotactile Haptic Feedback System For Proprioceptive Rehabilitation

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ABSTRACT The human sense of touch is an integral part of daily life. For tasks involving grasping and manipulation of objects, force feedback is a key requirement. Most of the systems give contact point or complete grasping force feedback; for precision grasping and other physical interactions, finger awareness and force feedback from independent fingers is essential. In this study a novel, wearable proprioceptive rehabilitation system is designed which restores the ability of identifying and distinguishing between individual fingers of a prosthetic hand or an exoskeleton in a non-invasive manner. Moreover, it provides different levels of force feedback from every finger as well, which enables the user to distinguish and control force in precision grasping activities. For testing the system accuracy, classical psychophysical methods were used on a group of 14 voluntary disabled subjects. The tests were conducted in both, ideal and real-world conditions i.e. without and with distractions and accuracies were calculated accordingly. A p-test was also conducted to observe significance between the samples of with and without distraction datasets. The system performed with an overall accuracy of 82.04% which was well above the min. performance measure of 60%. Vi-HaB is standalone system and can be mounted on any upper limb rehabilitation (prosthesis, exoskeleton) system for finger awareness and force feedback.

INDEX TERMS Wearable, haptics, vibrotactile, force feedback, Psychophysics, rehabilitation, virtual reality, Wilcoxon test.

I. INTRODUCTION

The importance of haptic force feedback in rehabilitation systems has been universally accepted and acknowledged [1] [2]. It has been proven to reduce their rejection ratio [3] [4] and increase the success rate in grasping and manipulation tasks [5]. It also results in alleviating both cognitive and muscular strain and induces a sense of embodiment [6] [7]. A lot of work is being done to replicate this uncanny, bio-inspired trait for disable people using various techniques which are broadly classified as invasive and non-invasive.

While reviewing these techniques in detail, both Antfolk et al. [8] and Li et al. [9] spoke in favour of non-invasive methods, arguing that invasive stimulation suffers from risks of infection and rejection, poor knowledge of neural decoding, technical issues of surgery, electrode replacement, and so on. Thus, non-invasive methods found way in most of the applications globally.

One of the oldest non-invasive techniques to be employed is the modality matched, mechanotactile feedback but with shifting trends Richard et al. [10], Antfolk et al. [8] and Li et al. [9] argued that to provide force feedback without sacrificing freedom of motion, the haptic interfaces have to be portable, lightweight and prevent user fatigue. This sent mechanotactile methods in background due to their relatively large size, weight and higher energy consumption, [8] [9] and sensory substitution methods came forward.

Sensory substitution revolutionized the field of wearable haptics with two key non-invasive techniques: electrotactile and vibrotactile feedback. Between these two, although electrotactile stimulation has the advantage of smaller size and relatively lower power consumption but small electrodes result in certain unexpected sensations such as burning pain; to counter which, larger electrodes need to be used. Another drawback is its interference with EMG and EEG signals [8]

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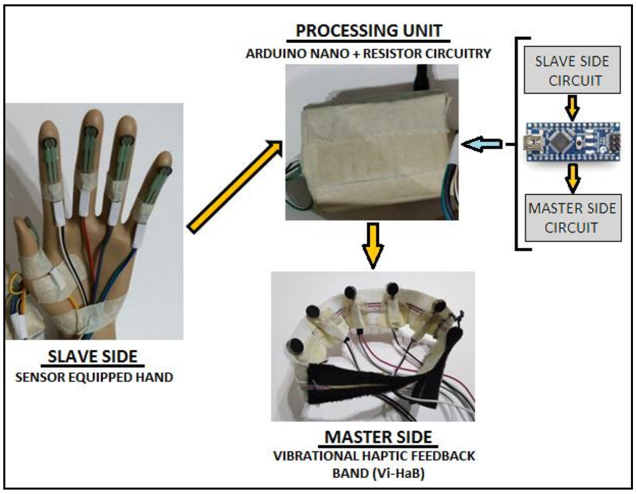

Fig. 1. System Block Diagram

[9] due to which vibrotactile stimulation, being free of the mentioned issues, found precedence in most applications.

Other reasons for the wide use of vibrotactile techniques are the ease of availability and integration with systems. Their relatively light weight property has opened new doors for wearable haptic devices [11] [12]. They are easily scalable; thus, are capable of displaying potentially larger amounts of data as compared to mechanotactile systems. [13] [8] [9] This scalability also results in the cost-effectiveness of the overall system [14]. Vibrotactile feedback is being used, both partially [15] [16] and independently [17] [18], in haptic systems as a force feedback channel.

Execution of tasks involving physical interaction with objects, specially of grasping and manipulation, is next to impossible without haptic feedback [1]. It is argued that not just the lack of overall grasping force but without awareness of individual fingers and independent force feedback from each, dexterity and precision in grasping cannot be achieved [19] [20]. Thus, it is imperative for the disabled person to have an awareness of each finger independently and then of the forces being applied from each [21] [22].

For individual finger awareness/stimuli localization, most of the existing systems utilize the phantom hand map as target points to deliver sensory feedback [23] [24] [25] [26] regardless of the fact that substantial number of amputees and all congenital amputees lack phantom hand map, thus leaving it as a feedback path with a dead end [27]. As a workaround to this limitation, different studies utilizing electrotactile [28] [29], vibrotactile and mechanotactile stimuli [28], have shown promising results that the brain can be taught to associate predefined areas on the skin with predefined stimulation areas.

In a recent, first of its kind study [30], this concept was explored by associating active locations on the forearm with specific fingers, using mechanotactile stimuli. Although the concept was practically verified but one major disadvantage of the system was that it was bulky owing to the five servo motors and thus did not qualify as a wearable system. The authors also declared mechanical noise generated by servo motors as another limitation which may have negatively impacted the learning process. Moreover, the system was only tested on able-bodies subjects, hence there was no insight as to how it would perform with amputees. In case of anything more than a trans-radial amputation, the system's response was undefined because it was only tested on the forearm.

So far, in light of the existing literature, no wearable system for providing finger awareness to amputees lacking phantom hand map is available. Thus, in this study we work on a unique system which rehabilitates the proprioceptive sense of individual finger identification, without the need of a phantom hand map. The system helps the user to associate fingers with active locations on the upper arm using vibrotactile stimulation.

In terms of force feedback, in recent years a lot of work has been done on force feedback from upper limb prosthesis using vibrotactile stimulation [31] [32]. Most of the systems have used either one [33] [34] [35] or two [36] [37] vibrotactile elements along with a single force sensor to convey complete grasping force and make or break contact information [38]. In case of single tactor, variation in frequency and amplitude represented different levels of force while with multiple tactors, each element represented a respective force level e.g. low and high. As the need for finer force level detection increased, the number of vibrotactile elements was also seen rising from three [39] [40] to eight [41] to an extent of up till twelve [42] in some cases. But since the target was to display complete grasping force so the number of force sensing element remained at a constant of one.

As seen from the existing literature review, studies have focused mostly on conveying complete grasping force feedback. In cases where the purpose is not to grasp the object but to use individual fingers, such feedback systems fail the user [43] [44]. Thus we focus on development of a system which rehabilitates the ability of sensing and distinction of force levels from every individual finger.

This study focuses on development and testing a novel, non-invasive, wearable vibrotactile haptic feedback (Vi-HaB) system which rehabilitates a disabled's proprioceptive sense, enabling them to identify and distinguish between individual fingers and multiple levels of force feedback from individual finger for upper limb rehabilitation systems i.e. prosthesis or exoskeletons.

Five force sensitive resistors FSRs, are mounted on a plastic, dummy hand; one FSR on each fingertip. This is to test the static interaction of the system for tactile sensory evaluation. Force feedback from these sensors is conveyed to the user through five vibrotactile motors within the wearable Vi-HaB band, thus establishing a one on one mapping between the slave and master sides. This one on one mapping also enables the system to provide an awareness of the individual finger thus making the disable person identify

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and differentiate between the respective (thumb, index, middle, ring and little) fingers on which forces are being applied. Each FSR – motor pair operates independently, allowing stimulations to be processed thus the system can provide multiple feedback forces simultaneously and complete grasping force feedback as well.

The system under discussion is a novel, haptic feedback system which rehabilitates the ability of identifying and distinguishing between individual fingers of a prosthetic hand or an exoskeleton in a non-invasive manner. This new mapping of fingers is not dependent on the phantom hand map thus is not limited to specific users. Moreover, it provides different levels of force feedback from every finger non-invasively, which enables the user to perform and control force in activities other than complete grasping, like typing and playing piano which do not involve the use of all fingers from the prosthetic hand or exoskeleton.

In short, Vi-HaB combines three types of proprioceptive information; individual finger awareness, force level detection at each finger and simultaneous force level detection, all in a single system. The static system is tested using tactile sensory evaluators to check whether the user is able to process and understand the provided haptic feedback information using the wearable band or not. The accuracy is calculated by conducting activities based on classical psychophysical methods on a group of 14 disabled subjects. The results are compared with predefined performance measures. A Wilcoxon signed rank test/ p-test is also conducted using MATLAB on the data samples.

The developed system is a non-invasive, proprioceptive rehabilitation system. It is wearable, low power consuming and free of mechanical noise. It does not interfere with EMG and EEG signals and is independent of phantom hand map limitations. It is a standalone system and can be mounted on any upper limb rehabilitation (prosthesis, exoskeletons) system for finger awareness and force feedback. It can also be used for force feedback in teleoperation systems and virtual reality.

II. MATERIALS AND METHODS

A. *Development of Haptic Feedback System - Vi-HaB*

The Vi-HaB system is developed to conveys force level information along with awareness of the finger they are being applied to. Static interaction takes places between the FSRs on fingertips of a plastic hand and tactile sensory evaluators. The system runs at an input of 5V and has three distinct units as shown in Fig. 1

1. Slave side.
2. Processing unit.
3. Master side.

The static slave side serves as a mount for the force sensors. Using different tactile sensory evaluators, static interaction is created which results in data output from the sensors. The data from these sensors is fed to a processing

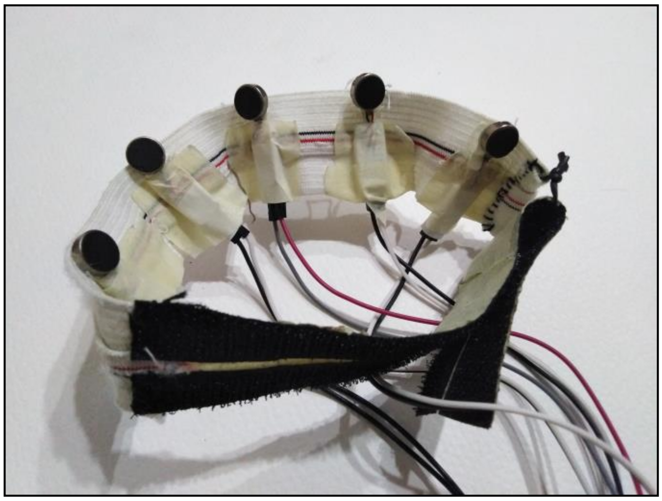

Fig. 2. Wearable vibrotactile haptic feedback band (Vi-HaB)

unit where it is converted into respective force levels. These levels are mapped, one on one, through the processor to the vibrotactile haptic feedback band on the master side. The wearable band serves to generate cutaneous signals as feedback from the sensors. Multiple vibrotactile motors are embedded within the band for this purpose. Each motor represents one finger and force levels are discriminated by variations in frequency and amplitude of vibrations.

The details of these three units are given in following subsections.

1) SLAVE SIDE

This side has five force sensitive resistors (FSRs) which serve as a link between the master side and the environment. These sensors are mounted on a plastic dummy hand; one sensor on each fingertip for testing static interactions and generating force feedback.

The FSRs used here are “Force Sensitive Resistors [45] – Small (SEN-09673 RoHS)” from Sparkfun [46] and are selected while keeping in view some key features. Each sensor has a 4 mm (0.16 in.) diameter active sensing area/spatial resolution. According to Li et al. [9], for tactile elements a spatial resolution of 5-40 mm can be considered satisfactory. What we have here is better than satisfactory.

Li et al. also states that the force sensitivity should be within the range of 0.3 to 10 N. Moreover, in another review article, Prachi Patel [47] states that according to the Revolutionizing Prosthetics Program (RPP) funded by DARPA, a bionic hand needs to feel a minimum of 0.1 N of force over a fingertip. The actuation force of the FSRs used here is 0.1 N with a sensitivity range of 0.1 to 10 ± 2% N, thus the range of these sensors is meeting international standards.

The sensors are set in a directly proportional configuration where the output voltage increases with increase in the applied force [48]. The output voltages of sensors are fed, through a supporting circuitry, to a microcontroller in the

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TABLE I
VI-HAB COST BREAKDOWN

Component name	Quantity	Per unit cost (USD)	Total cost (USD)
Force Sensitive Resistors, Small (SEN-09673 RoHS)	5	$8	$40
Arduino Nano breakout board	1	$6	$6
Coin vibration motors	5	$1.6	$8
Miscellaneous (wires, connectors, resistors, transistors etc)	-	-	$4
Total system cost			$58

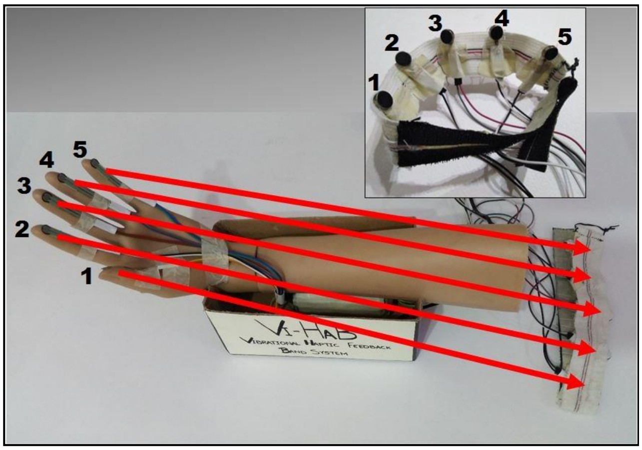

Fig. 3. Vi-HaB System

processing unit where they are converted into respective force levels.

2) PROCESSING UNIT

The processing unit is a square cardboard box which houses the slave side circuitry, the master side circuitry and a microcontroller. It is a small 3.5 x 2.5 x 1.8 in. unit with an operating voltage of 5V.

An Arduino Nano microcontroller serves as the link between the slave and master side. Its small size and low power consumption fulfills the requirements of the system.

The outputs from FSRs are received by the microcontroller. It converts the sensor voltages and maps them, one on one, to the master side vibrotactile motors through the connecting circuitry.

3) MASTER SIDE

The Master side consists of the main, wearable Vibrotactile haptic feedback band (Vi-HaB) as shown in Fig. 2. It is a 15 x 1 in. band, in which 7.5 in. is nylon elastic while the remaining is adjustable velcro so that it can be altered according to the ease of different users.

This band wraps around the upper arm thus is capable of facilitating all amputees below shoulder disarticulation. Moreover, in a study conducted by P. Chaubey et al. the results show that the biceps region is most preferred in terms of resolution and user preference for placement of a vibrotactile feedback device [49].

Five vibrational coin motors are equally spaced on the 7.5 in. elastic portion with a gap of approx. 25.4 mm (edge to edge) between each. This distance is in conformity with the human detection thresholds. For single stimuli at a time, J. Rantala [50] states the minimum point localization distance to be 15 mm while in case of multiple stimuli, Michael et al. [51] identifies the minimum distance for two-point discrimination to be more than 20 mm. Hoffmann et al. [52] states the closest distance physically possible is 10 mm for vibrotactile elements. They accessed vibrotactile spatial acuity at both 20 mm and 10 mm distance; the 20 mm distance lead to about 64% discrimination accuracy. As the vibrotactile motor's distance in Vi-HaB is more than the minimum mentioned here, so an accuracy of at least above 65% is predicted.

The motors used in Vi-HaB have a diameter of 10.0 mm and 3.0 mm height. The operating voltage is 1.5 - 4V and a stall current of 0.06 A [53]. Each motor is linked to one FSR from the slave side through the Arduino board via the supporting circuitry. Each motor, thus, represents one finger of the hand. Simultaneous variations in both frequency and amplitude of the motor represent the force levels being applied on the fingertips of the dummy hand. The ranges for frequency and amplitude variation of motors are [~95 - ~240] Hz and [~0.2 - ~0.65] g respectively. [54] [55] [56]

These motors activate the Pacinian corpuscles, FA II type mechanoreceptors, in the skin as the frequency range is well within the range detected by them i.e. ~40 to ~400 Hz. According to Lederman et al. [57] the advantage of operating in the FA II type range is that their adaption time is fast. This reduces the overall system training time.

B. *Vi-HaB*

The three modules discussed above, slave side, processing unit and master side combine to form the complete Vi-HaB system as shown in Fig. 3. Five FSRs and motors are mapped, one on one, onto each other thus each motor represents an individual finger of the dummy hand. The wearable band wraps around the upper arm such that each motor falls in line with the natural position of the fingers as shown with red arrows in Fig. 3. thus, it helps in development of mapping within the user's mind.

Each motor's variation in vibrational intensity represent different force feedback levels. The relation between motor vibrations and applied force is directly proportional and is given by the following formula:

$$V_{out} = V_{in}/[1 + (R_{FSR}/R_M)] \qquad (1)$$

Where $V_{in} = 5V$ and $R_M = 3.3k\Omega$

A cost breakdown of the system has been provided in Table I.

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C. SUBJECTS

The Vi-HaB was tested on 14 disable subjects in collaboration with Armed Forces Institute of Rehabilitation Medicine (AFIRM). The subjects' ages ranged between 15 to 41 years with three females and remaining male. All subjects had some form of disability i.e. amputation or nerve injury. Details about their type of disability, effected hand and dominant hand are given in Table II.

They were briefed about the details of system, the testing process and a consent form was signed with them, prior to the activity. All tests were conducted in accordance with the rules and guidelines of ethics committee at AFIRM and the Declaration of Helsinki.

D. TESTING OF Vi-HaB

Once the system is ready, it is necessary to test whether the claimed types of haptic information are distinguishable by the user or not. And if, as theoretically expected, the user is perceiving the feedback correctly then what level of accuracy is being achieved. If the system accuracy is not above a certain predefined performance measure, then it summarizes that it cannot be used in practical life.

The universally accepted techniques for testing the sensitivity and accuracy of haptic systems are the Psychophysical Methods. In this study, one of the techniques from the classical psychophysical methods has been used. [58] [59]

As mentioned, Vi-HaB is aimed to deliver three types of haptic information, thus the accuracy of system for each type was tested by conducting individual activities for each. For testing the system, three sets of activities were designed using the "Method of Constant Stimuli". This method has two further variations. The first two activities followed the "Absolute Threshold (RL)" test i.e. "Method of successive Constant Stimuli" while the third activity followed the "Differential Threshold (DL)" test i.e. "Method of simultaneous Constant Stimuli." [60].

These activities were conducted with each subject individually. The system setup for testing can be seen in Fig. 4. The subject's disabled/residual arm is placed parallel to the stump of dummy hand. A black cloth is used to cover the stump so as to induce a sense of embodiment. Vi-HaB band is wrapped around the subject's upper arm. A removable opaque white flexible screen is used to hide the hand from the subject's view.

A predefined set of stimuli are presented to the user by static interaction between dummy hand and tactile sensory evaluators (Fig.5). Tactile sensory evaluators are used to maintain uniformity of stimuli across all subjects.

They are first trained on the system and then the activities are conducted. Each activity is subdivided into two cases. In first case, the activity is conducted in a quiet and distraction free environment using noise cancellation headphones. A five-minute time gap is added to check whether the subject retains the developed mapping. Then the subject's environment is introduced with audiovisual distraction by playing an animated video on a laptop screen and headphones are used as audio output. The distractions are to check the effect of external disturbances on Subject's perceptual ability.

TABLE II
VOLUNTARY SUBJECTS DETAILS

Subject Number (S)	Gender (M/F)	Age	Disability	Testing/ effected Arm	Dominant hand
1	F	15	Wrist amputation	Right	Right
2	M	17	Trans-radial congenital amputation	Left	Right
3	M	19	Wrist amputation	Right	Right
4	F	21	Trans-radial amputation	Left	Left
5	M	24	Trans-carpal amputation	Right	Right
6	M	26	Trans-humeral amputation	Left	Right
7	M	27	Brachial Plexus injury	Right	Left
8	F	30	Trans-radial amputation	Left	Right
9	M	31	Trans-radial amputation	Left	Left
10	M	31	Nerve injury	Left	Right
11	M	32	Trans-radial amputation	Right	Right
12	M	32	Brachial Plexus injury	Right	Right
13	M	34	Trans-humeral amputation	Left	Right
14	M	41	Trans-radial amputation	Right	Right

The distraction free environment is an ideal, lab condition but in real world, the subjects experience many visual distractions in form of moving objects and audio distractions in forms of random sounds. The subject's attention gets divided involuntarily which can affect his ability to successfully discern the haptic ques. Moreover, while performing any primary activity, like watching television, if the subject performs any secondary activity with their hand, involving Vi-HaB system, they should be able to successfully distinguish the haptic ques even with divided attention. For a system to be effective, it should either work equally well or outperform in a distractive environment. Thus, every activity is conducted with distractive conditions to observe their effect on system accuracy.

The complete test with one individual is for a duration ranging from 45 minutes to 1 hour, depending on subject's adaptability to the system. The subjects are asked to give verbal responses during the activities, which are recorded in tabular forms.

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Fig. 4. Vi-HaB system testing setup

A standardized scoring method for activities is set to calculate the system accuracy. The results are then compared with predefined performance measure/minimum accuracy requirements.

Details of tactile sensory evaluators, activities, how they were conducted and scored, and the Wilcoxon double-sided signed rank test are given in following subsections.

1) TACTILE SENSORY EVALUATORS

Data generated from human observers is often highly variable; like other analytical test procedures, sensory evaluation is concerned with precision, accuracy, sensitivity and the avoidance of false positive results [61]. In field of touch, tactile sensory evaluators are used to determine specific relationship between stimuli and human perception [62] [63] [25] [64].

In this study, three clip type tactile evaluators are used where each induces a specific stimuli i.e. low, medium and strong level force. The evaluator clips can be seen in Fig. 5. Each clip has a specific spring strength thus when placed on the fingertip, it induces a specific level of force. Low-level clip induces a force of approx. 1 – 2 N, medium-level clip induces a force of approx. 4 – 5 N and strong-level clip induces a force of approx. 7 – 8 N. Each clip's contact area, 10.2 mm x 0.9 mm, with the FSR is fairly small which ensures repeatability and uniformity of contact points every time it is placed over the sensor.

These ensure the presentation of uniform stimuli to all subjects.

2) ACTIVITY I: INDIVIDUAL FINGER DETECTION

a) SYSTEM TRAINING

Subjects are given an initial training on Vi-HaB for individual finger identification of the dummy hand. A duration of 10 minutes was set as maximum for the training activity. The band is wrapped on subject's arm and they are able to see dummy hand. Each finger is pressed sequentially using the medium-level tactile evaluator clip while the subject visually observes and develops a feel of the location of respective vibrating motor.

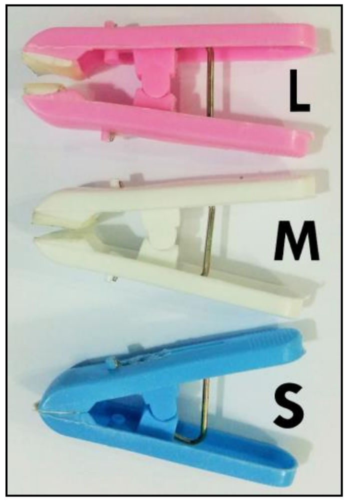

Fig. 5. Tactile sensory evaluator clips

Before placing the clip on each fingertip, a cue is also given by announcing the finger being pressed i.e. thumb and then 1 to 4 for the remaining fingers respectively. The clip is left on the fingertip for 1 second before removing it. Each successive stimulus is presented with a gap of 5 second in between.

The subject is first presented with 3 training cycles, where one training cycle is equal to a complete circuit of stimuli presented from thumb to last finger and then back to thumb.

After this, a random order is presented on subject's request. The activity is conducted after the subject gives a go ahead, within the specified time of 10 minutes.

b) SYSTEM TESTING

(a) CASE I: WITHOUT DISTRACTION

After the training session, the dummy hand is hidden from the subject's view by placing an opaque white sheet in front but the user can still look at the Vi-HaB band. A noise cancellation headphone is placed on the subject's ears for distraction free environment. Using the medium-level evaluator clip a total of 30 stimuli are presented to each subject.

These 30 stimuli are divided into 6 groups where each group has the same set of stimuli but with different random order. Each group consists of same five stimuli where 'Th' stands for 'Thumb', '1' for index finger, '2' for middle finger, '3' for ring finger and '4' for little finger. These groups are mentioned in the Table II(a).

The whole table of 30 stimuli is presented to each subject without any cue in a distraction free environment. Each stimulus is held for 1 second and then subject's verbal response is anticipated in the next 5 seconds. The subject is to verbally announce which finger was pressed. In case of no response, the same stimulus is repeated once. For every

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TABLE III
INDIVIDUAL FINGER DETECTION ACTIVITY

(a) Case I: Without Distraction

GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5	GROUP 6
TH	1	3	4	TH	2
3	2	2	TH	1	4
1	TH	4	2	3	1
2	3	1	3	4	TH
4	4	TH	1	2	3

(b) Case II: With Distraction

GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5	GROUP 6
3	TH	TH	2	1	4
2	1	3	4	2	TH
4	3	1	1	TH	2
1	4	2	TH	3	3
TH	2	4	3	4	1

TABLE IV
FORCE LEVEL DETECTION ACTIVITY

(a) Case I: Without Distraction

FINGER 1	FINGER 3	FINGER 2	THUMB	FINGER 4
S	M	L	M	S
L	L	M	S	M
M	S	L	L	M

(b) Case II: With Distraction

FINGER 4	THUMB	FINGER 3	FINGER 1	FINGER 2
L	S	S	M	M
M	M	L	S	L
L	M	M	L	S

correct or wrong response, a tick or cross is marked across the respective stimuli in the table and the next stimuli is presented.

(b) *CASE II: WITH DISTRACTION*

After the above, without distraction activity, the subject's environment is introduced with audiovisual distraction by playing an animated video on a laptop screen while the audio is supplied through the headphones. The subject is now asked to only concentrate on the video and not look elsewhere. The hand is still kept hidden from view using the same opaque sheet.

Same activity as above, Case I, is conducted again. 30 stimuli are presented to the subject again but with audiovisual distraction this time. The orders of stimuli within each group are shuffled as from the previous, without distraction, case to avoid the chance of anticipation by the subject in case of a subject with exceptional memory. The stimuli presented in this case are given in Table II(b). The subject's verbal responses are anticipated and recorded in the same way as was done in the previous case.

(c) *ACTIVITY SCORING*

Each correct response in the activity is given a weight of 1. Number of correct responses are marked out of a total score of 30 for each case.

3) *ACTIVITY II: INDIVIDUAL FORCE LEVEL DETECTION*

a) *SYSTEM TRAINING*

After completing Activity - I, the noise cancellation headphones are removed so that the subject can listen to the experimenter's explanation. The subject is given a training on Vi-HaB for detection of forces applied on each fingertip of the dummy hand. A duration of 10 minutes was set as maximum for the training activity. The force training activity is conducted by applying three levels of force on individual fingers, sequentially, while the subject develops a feel of the difference in force levels based on vibrational intensities. These forces are presented using the three tactile evaluator clips. The subjects are to distinguish between three levels of force

- Low (L)
- Medium (M)
- Strong (S)

Before placing each evaluator clip, a verbal cue is given by announcing it i.e. Low, Medium, Strong and is held for 1 second. Each successive stimulus is presented with a gap of 5 seconds in between. Subject is first presented with 3 training cycles, where one training cycle is equal to a complete circuit of force stimuli (from low to strong) on each finger.

After this, random orders are presented on subject's request. The activity is conducted after the subject gives a go ahead, within the specified time of 10 minutes.

b) *SYSTEM TESTING*

(a) *CASE I: WITHOUT DISTRACTION*

After the training session, the noise cancellation headphone is placed on the subject's ears for distraction free environment. The dummy hand is kept hidden using the

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TABLE V
SIMULTANEOUS MULTIPLE FORCE LEVEL DETECTION ACTIVITY

(a) Case I: Without Distraction

GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5
TH - S	1 - M	2- M	1 - L	2 - S
4 - L	3 - L	3 - S	4 - M	4 - M

(b) Case II: With Distraction

GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5
2- M	2 - S	TH - S	1 - L	1 - M
3 - S	4 - M	4 - L	TH - M	3 - L

opaque sheet. Using all three evaluator clips a total of 20 stimuli are presented to each subject.

These 20 stimuli are divided into 5 groups where each group represents one finger. Within each group, three force stimuli are presented randomly on a finger. As shown in Table III(a), 'L' represents low, 'M' represents medium and 'S' represents strong and for presenting each of these stimuli, the respective evaluator clips, low-level, medium-level or strong-level are used.

First a pulse is given on the finger mentioned in the table and the subject is to determine and announce the finger being pressed. The response is marked with either a tick or cross mark in the table. After that, force levels are presented without any verbal cue with a gap of 2 second between each stimulus on the same finger. Subjects are asked to wait for all three force stimuli and then subject's verbal response is anticipated in the next 5 seconds. The subject is asked to verbally announce the sequence of stimuli that were presented from first to last. In case of no response, the same sequence is repeated once. For every correct or wrong response, a tick or cross is marked against the respective stimulus in the table and the next sequence is presented.

The whole table of 20 stimuli is presented to each subject without any cue in a distraction free environment.

(b) *CASE II: WITH DISTRACTION*

After the above, without distraction activity, the subject's environment is introduced with audiovisual distraction by playing an animated video on a laptop screen while the audio is supplied through the headphones. The subject is now asked to only concentrate on the video and not look elsewhere. The hand is still kept hidden from view using the same opaque sheet.

Same activity as above, Case I, is conducted again. 20 stimuli are presented to the subject but with audiovisual

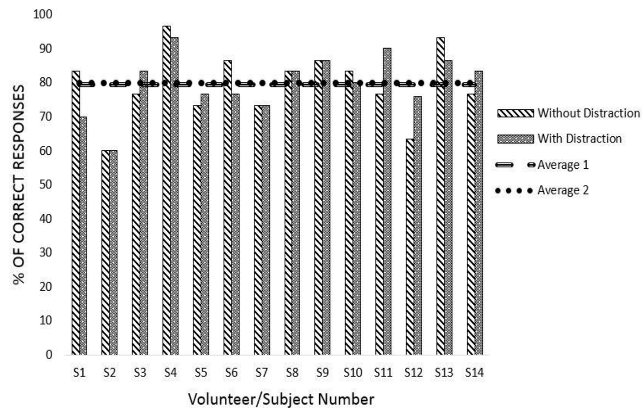

Fig. 6. Individual finger detection activity

distraction this time. The orders of stimuli within each group are shuffled as from the previous, without distraction, case to avoid the chance of anticipation by the subject in case of a subject with exceptional memory. The stimuli presented in this case are given in Table III(b). The subject's verbal response is anticipated and recorded in the same way as was done in the previous case.

(c) *ACTIVITY SCORING*

Each correct response in the activity is given a weight of 1. Number of correct responses are marked out from a total score of 20 for each case.

4) *ACTIVITY III: SIMULTANEOUS FORCE LEVEL DETECTION*

a) *SYSTEM TRAINING*

After completing Activity - II, the noise cancellation headphones are removed so that the subject can listen to the experimenter's explanation. The subject is given training on Vi-HaB for identifying two spatially displaced force stimuli presented together. A duration of 10 minutes was set as maximum for the training activity.

The training activity is conducted by applying two different stimuli simultaneously on two random fingers, while the subject is asked to identify just the two different force levels being applied. Subject is presented with 5 stimuli pairs in random order on random finger. These stimuli are presented using any two of the three tactile evaluator clips at a time.

Before presenting the stimuli, the two force levels are verbally announced. Each successive stimulus pair is presented with a gap of 5 seconds in between. The activity is conducted after the subject gives a go ahead, within the specified time of 10 minutes.

b) *SYSTEM TESTING*

(a) *CASE I: WITHOUT DISTRACTION*

After the training session, the noise cancellation headphone is placed on the subject's ears for distraction free

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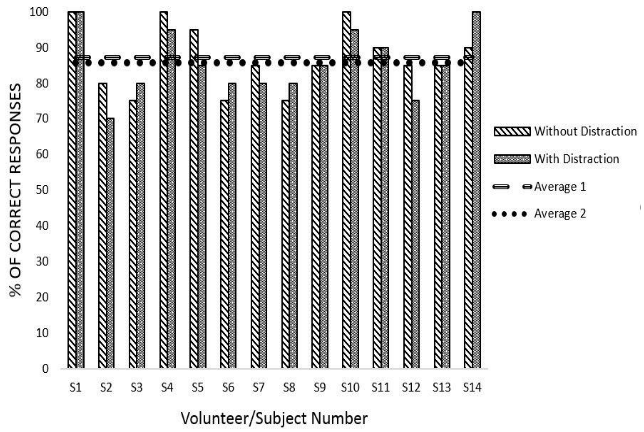

Fig. 7. Force level detection activity

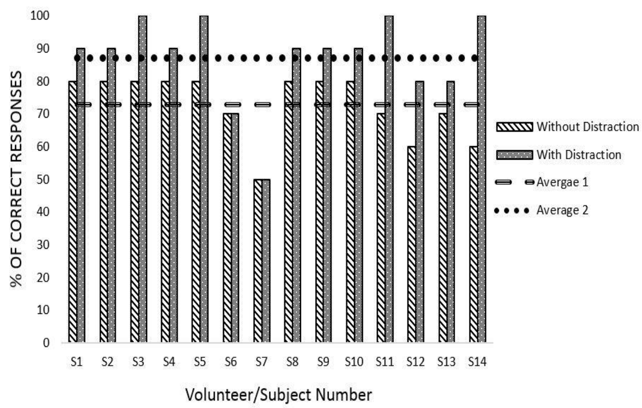

Fig. 8. Simultaneous force level detection activity

environment. The dummy hand is kept hidden using the opaque sheet. Using all three evaluator clips a total of 10 stimuli are presented to each subject.

These 10 stimuli are divided into 5 groups, where each group has one set of stimuli as shown in Table IV(a). In each group, the stimuli are marked as 'X - Y' where X represents the finger on which the stimuli is being presented and Y represents the evaluator clip/force level that is being presented on the respective finger. The subject is only to identify the level of two simultaneous stimuli being presented i.e. a combination of any two out of the three force levels (low, medium, strong).

Two stimuli within each group are simultaneously presented to the subject. He is asked to announce just the force levels of simultaneous stimuli that are felt and the verbal response is anticipated in the next 5 seconds. The subject is to verbally announce the level of two stimuli that are presented. In case of no response, the same sequence is repeated once. For every correct or wrong response, a tick or cross is marked on the respective stimulus in the table and the next sequence is presented with a gap of 5 seconds.

(b) ***CASE II: WITH DISTRACTION***

After the above, without distraction activity, the subject's environment is introduced with audiovisual distraction by playing an animated video on a laptop screen while the audio is supplied through the headphones. The subject is now asked to only concentrate on the video and not look elsewhere. The hand is still kept hidden from view using the same opaque sheet.

Same activity as above, Case I, is conducted again. 10 stimuli are presented to the subject again but with audiovisual distraction this time. The orders of stimuli within each group are shuffled as from the previous, without distraction, case to avoid the chance of anticipation by the subject in case of a subject with exceptional memory. The stimuli presented in this case are given in Table IV(b). The subject's verbal responses are anticipated and recorded in the same way as was done in the previous case.

(c) ***ACTIVITY SCORING***

Each correct response in the activity is given a weight of 1. Number of correct responses are marked out from a total score of 10 for each case.

E. *SYSTEM ACCURACY*

Subjects' score in activities are individually calculated by finding out the percentage of correct response in both cases.

$$Subjects'\ Score = \%\ of\ correct\ responses =$$

$$\frac{No.of\ correct\ responses}{Total\ Activity\ Score} x\ 100 \quad (2)$$

Accuracy of individual test case (without distraction, with distraction) is calculated by averaging all the Subjects' Scores.

$$Accuracy\ of\ test\ case = \frac{\sum of\ Subjects\ score}{No.of\ subjects} \quad (3)$$

A comparison is drawn between the systems performance for without and with distraction cases.

The accuracy of system for individual activities is calculated by averaging the percentage accuracies of both cases.

$$Accuracy\ of\ activity = \frac{\sum of\ \ accuracy\ of\ test\ cases}{2} \quad (4)$$

Overall system accuracy is calculated by averaging the accuracy of all activities

$$System\ Accuracy\ = \frac{\sum of\ \ accuracy\ of\ activities}{3} \quad (5)$$

F. *PERFORMANCE MEASURE OF THE SYSTEM*

According to the performance measure set for the developed system, the accuracies of Activity I and II should be above 50%.

This benchmark percentage has been selected from the performed "Method of constant stimuli (RL)" according to

TABLE VI
RESULTS

Activity	Accuracy in Cases: Without Distraction (%)	Accuracy in Cases: With Distraction (%)	Net Accuracy in activity (%)	Error (%)	Performance Measure
Individual Finger Detection	79.48	79.92	79.70	-0.44	50
Force Level Detection	87.14	85.71	86.43	1.43	50
Simultaneous Force Level Detection	72.86	87.14	80	-14.29	70
		Overall System Accuracy (%)	82.04		60

which, the intensity where the proportion of correct responses is 0.5 is taken as the "Absolute Threshold (RL)".

So, if a haptic system has an accuracy above this level i.e. 50%, then it points to the fact that it is operating above the absolute threshold and all the incoming stimuli will be easily detected. [65]

For Activity III, the accuracy should be above 70% because the "Difference Threshold (DL)" is the intensity where the percentage of correct responses is ~70%. So, an accuracy value above this level shows that the incoming stimuli will be successfully distinguishable from each other. [60].

Since the performance measures for activities are not uniform thus the performance measure for overall system is defined as 60%, the average value of these two benchmarks, 50% and 70% i.e.

III. RESULTS AND DISCUSSION

Subjects scores for activities I, II and III have been presented in a bar graph format in Fig. 6, Fig, 7 and Fig. 8 respectively. The x-axis represents the subject number, S1 – S14. Each bar set along the y-axis shows the subject's score out of 100%, in both without and with distraction cases. Two horizontal lines, parallel to x-axis, Average 1 and Average 2, show the average of all the subjects scores, in both, without and with distraction cases respectively.

Accuracies of activities are also shown in Table V. For "Individual finger detection activity", the system accuracy in case I (without distraction) is 79.48%. While in case II (with distraction), it is 79.92%. The Net accuracy of system in this activity came out to be 79.70%.

For "Force level detection activity", the system accuracy in case I (without distraction) is 87.14%. While in case II (with distraction), it is 85.71%. The Net accuracy of system in this activity came out to be 86.43%.

The accuracy values in both these activities, I and II, are well above the set performance measure i.e. 50%.

In the above mentioned two activities, I and II, it is observed that the performance mildly improved and deteriorated by a percentage of -0.44 and 1.43 respectively, after the addition of distraction to the system; which is negligible. This negligibility claim is supported by the Wilcoxon test results. A significance analysis is conducted between data of with and without distraction cases for all subjects with a significance value of 0.05. The h-value gives a logical 0 for both activities I and II with p-values of 0.8613 and 0.4629 respectively, thus verifying the null hypothesis; meaning that there is essentially no difference in the system's performance with or without distraction.

For Simultaneous force level detection activity, the system accuracy in case I (without distraction) is 72.86% while in case II (with distraction), it is 87.14%. The Net accuracy of system in this activity came out to be 80% which is well above the set performance measure of 70%.

This activity exhibits a unique phenomenon of significantly large negative error of -14.29%. This shows that the system performance improves after the addition of distractions. The result of Wilcoxon test conducted between the data of all subjects for with and without distraction cases in this activity also verifies the difference when the h-value gives out a logical 1 with a p-value of 4.8828e-04.

This is because the spatial acuity feedback of skin is better than vision in presence of a reference factor [57]. When there is no distraction, the subject unconsciously tries to judge by looking at the band. But when distraction is added, it severs the visual link and subject inherently relies on feedback from the skin. Moreover, the simultaneous forces complement and serve as a reference to each other, as intended by the DL

TABLE VII
WILCOXON'S SIGNED RANK TEST

Activity	Wilcoxon Test: p	Wilcoxon Test: h (Logical)
Individual Finger Detection	0.8613	0
Force Level Detection	0.4629	0
Simultaneous Force Level Detection	4.8828e-04	1

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2020.2975149, IEEE Access

activity, which makes it easier for the subjects to discern the level. Thus the accuracy improves.

The overall accuracy of Vi-HaB system is 82.04%. This value is well above the performance measure for the overall system i.e. 60%.

IV. CONCLUSION

In this study, a wearable vibrotactile haptic feedback system is designed for proprioceptive rehabilitation in upper-limb rehabilitation systems. The system combines three important types of haptic feedback information that are individual finger awareness, force feedback from every finger independently and using the same system, simultaneous force feedback i.e. the overall grasping force can also be made known to the user.

The accuracy of Vi-HaB is tested by conducting three sets of activities with a group of 14 disable subjects. Each activity is used to evaluate the accuracy of the system for generating a specific type of feedback information. Individual accuracies are calculated for each type of haptic information being presented. Moreover, the overall accuracy of the system is also calculated which is 82.04%. This value is found to be well above the set minimum performance measure for the system i.e. 60%. A statistical analysis is also conducted between the dataset collected under two different conditions; one being the without distraction case and the other, with distractions. The results show that the system is fit to use in both lab and real-world conditions, without any deterioration in performance.

This study also verifies the assumption made by Wijk et al. [30] that the training time, for associating predefined points on arm with fingers, in amputees as compared to able-bodies subjects should be less. In the study, with able-bodied subjects [30], it took approx. 20 minutes to complete the training session for one activity, as compared to this study with amputees where the maximum duration for training session of an activity is 10 minutes.

It is evident that this vibrotactile rehabilitation system can be used to associate active points on the upper arm with fingers. It can be integrated with rehabilitation systems i.e. in upper limb prosthesis and exoskeletons for force feedback from individual fingers.

It is a novel, wearable proprioceptive rehabilitation system which restores the ability of identifying and distinguishing between individual fingers of a prosthetic hand or an exoskeleton in a non-invasive manner. It is not limited to the availability of a phantom hand map for its operation. Moreover, it provides different levels of force feedback from every finger as well, which enables the user to perform and control forces in precision grasping activities.

In future, the developed system can be used to explore other prospective feedback locations on the human body such as the neck, abdomen or thigh. By placing the wearable band at different locations on the body, system's response and accuracy can be found by using the same method as defined in this study and their results can be compared. This will aid in selecting the appropriate vibrotactile feedback location in case of subjects with shoulder disarticulation and brachial plexus injury.

The system in this study provides force feedback to the subjects but it has not been tested for force control with an active prosthesis or an exoskeleton. Thus in future, its effect on real time force control of rehabilitation systems can be studied by mounting it on an EMG controlled prosthesis or an exoskeleton. By conducting basic grasping activities and observing the number of successful grasps in minimum time with and without the Vi-HaB system, its effect on the force control and operation can be measured.

By observing the system's response on able bodies subjects, its use for force feedback and control in teleoperation grippers can also be tested. The current system is an altogether wired network which limits it for short range teleoperations but in future, by establishing a wireless (Bluetooth or Wi-Fi) link between the wearable band and the processing unit, it can be tested for feedback in long range teleoperation activities as well.

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